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Centrifuge Testing of a Bridge Pier on a Rocking Isolated Foundation Supported On Unconnected Piles

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ABSTRACT

A preceding experimental study carried out at the University of Dundee, as well as independent experimental and numerical research results, have shown the improved seismic performance of rocking shallow foundations in comparison to conventional, conservatively designed foundations, for bridges. By properly reducing the size of the footing, rocking behaviour due to seismic loading can occur about the footing base. It has been shown that rocking foundations can reduce seismic ductility demand on bridge columns and improve bridge performance so much so as to enable them to safely resist very strong seismic motions which lead to collapse of alternative conventional systems. Yet, key concern is the potential for significant settlement accumulation, especially in relatively poor soil conditions. Therefore, current research objectives focus on exploring possible innovative foundation systems that will optimise the seismic performance of rocking foundations. To this end, a series of dynamic centrifuge tests on 1:50 scaled bridge piers on sand were performed. This paper presents results for only one of the investigated alternatives: the rocking foundation is supported by a 4x4 group of unconnected reinforced concrete (RC) piles. Comparative evaluation of the performance of this hybrid foundation system indicates significant reduction of settlements, yet at the cost of increased deck drift. It is shown that particular care must be taken in designing such foundation systems to retain the total moment capacity low enough to prevent damage of the supported column.

Introduction

In recent years, a significant amount of research evidence [e.g. Gajan et al., 2005; Gajan & Kutter 2008; Anastasopoulos et al., 2010; and Gelagoti et al., 2012] has highlighted the potential of a new foundation design concept: deliberately under-designing shallow foundations to promote nonlinear rocking oscillations. Termed *rocking isolation*, this relatively new idea has the potential to drastically improve the seismic resilience of structures. The key concept underpinning this design approach is that the yield moment within the foundation is lower than that which causes damage in the supported column or pier, resulting in shallow foundations which are smaller than those produced by conventional approaches (where the aim is to prevent the foundation from moving significantly).

A recent collaborative research has been undertaken between the National Technical University of Athens and the University of Dundee (UoD) to study the possible implementation of the rocking isolation concept on the design of modern well-confined, Eurocode 2/8 compliant, reinforced concrete (RC) bridge structures involving primarily dynamic centrifuge model tests and accompanying numerical modelling. During this study,

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the model bridge piers were realistically modelled using a novel scale-model reinforced concrete developed at Dundee and described in Knappett et al. [2010; 2011] and Al-Defae &Knappett [2014]. A series of tests were conducted on appropriately scaled 1:50 bridge pier models standing upon a layer of medium density sand. The tests involved identical piers supported on alternative foundation systems. Loli et al. [2014] report the results for the case where the piers are supported by rectangular shallow foundations considering two different foundation sizes, the conventional foundation (7.5 m x 7.5 m) and the rocking isolated one (4 m x 4 m), and are subjected to a variety of real earthquake ground motions of different intensities. The results clearly demonstrate consistently beneficial performance of the rocking isolated piers in terms of inertial loads transmitted to the superstructure as well as deck drifts. Most importantly, owing to nonlinear foundation rocking response, a pier standing on an under-designed foundation proved capable of surviving even deleterious earthquake scenarios, with minimal structural distress, while the alternative conventional pier suffered catastrophic damage or even collapse.

Yet, exhibiting what is known as “sinking response” the rocking foundation was found to accumulate significant settlement, this being identified as the only drawback of the rocking isolation design. Naturally, owing to its significantly lower FS_V the rocking foundation is prone to suffering increased settlements in comparison to the over-designed foundations involved in conventional capacity design. To remediate this, a number of improved “hybrid” foundation systems were developed, where it was attempted to combine rocking response, and its advantages for the superstructure, with soil improvement to reduce settlements. This paper presents one of these attempts where a 4 x 4 group of unconnected piles is used to enhance the foundation area. Figure 1 depicts the main features of the studied problem indicating RC section properties and select problem parameters. It should be observed that an intermediate very shallow layer of dense sand (D_r = 80%) was used between the footing and the pile group to ensure a uniform and level foundation area.

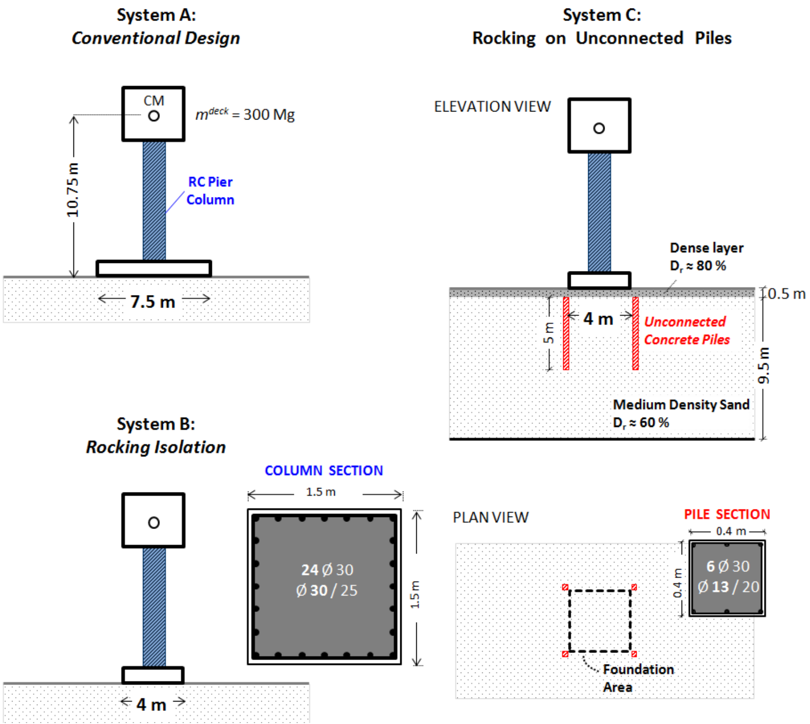

Figure 1. Schematic definition of the studied problem: comparison of three alternative foundation designs for a moderately tall highway bridge pier.

Centrifuge Modelling

Results from three dynamic centrifuge tests are presented. These were conducted on 1:50 scale physical models of the bridge pier system, with identical super-structural properties, but with different foundations. In each case, the structures were placed on dry fine Congleton silica sand (HST95, γ_{max} = 1758 kg/m3, γ_{min} = 1459 kg/m3, D_{60} = 0.14 mm, D_{10} = 0.10 mm, critical state friction angle ϕ'_{crit} = 32°), prepared uniformly by air pluviation to a relative density, Dr ≈ 60% (or 80% for the shallow layer of soil improvement). The sand deposit was 200 mm deep (i.e., 10 m at prototype scale) and was prepared within the equivalent shear beam (ESB) container described by Bertalot [2012] to minimize dynamic boundary effects. Instrumentation consisted of 13 type ADXL78 MEMS accelerometers (± 70-g range) and Linear Variable Differential Transformers (LVDTs). The models were loaded onto the UoD beam centrifuge and Actidyn Q67-2 servo-hydraulic earthquake simulator. Figure 2 shows a photo of one of the models before testing.

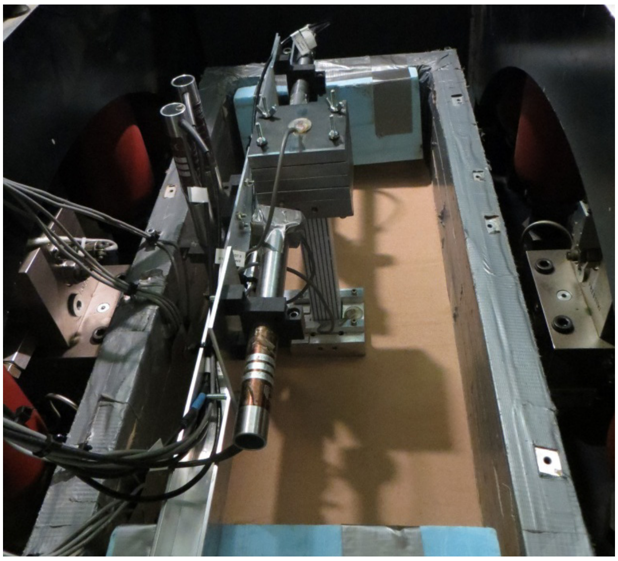

Figure 2. One of the models within the ESB container mounted on the centrifuge.

Both the pier column, where structural damage is expected, and the piles were modelled using a novel scale-model concrete which reasonably predicts the response and failure of reinforced concrete elements. The model was developed by Knappett et al. [2010] and validated against element bending tests of the pier column and theoretical section analysis predictions Loli et al., [2014]. It involves appropriately scaled down models of: (i) the cementious binder, using a gypsum-based mortar; (ii) the aggregates, using silica sand; and (iii) the reinforcement, using stainless steel wire. Fabrication of the reinforcement assembly was challenging due to the scale of the produced columns. The 200 mm long column model contained a total length of more than 5 m of wire modeling longitudinal reinforcement and forty five shear links uniformly spaced at a distance of approximately5 mm. Anchoring of longitudinal reinforcement was achieved by providing an additional length of about 10 mm on each side of the column, which was bent and fixed within the foundation or the deck plates. Figure 3 shows photos from different stages of the model concrete elements construction. Test units were cast in custom-built formworks (Fig. 3a, and 3e) which allowed casting of two columns at a time.

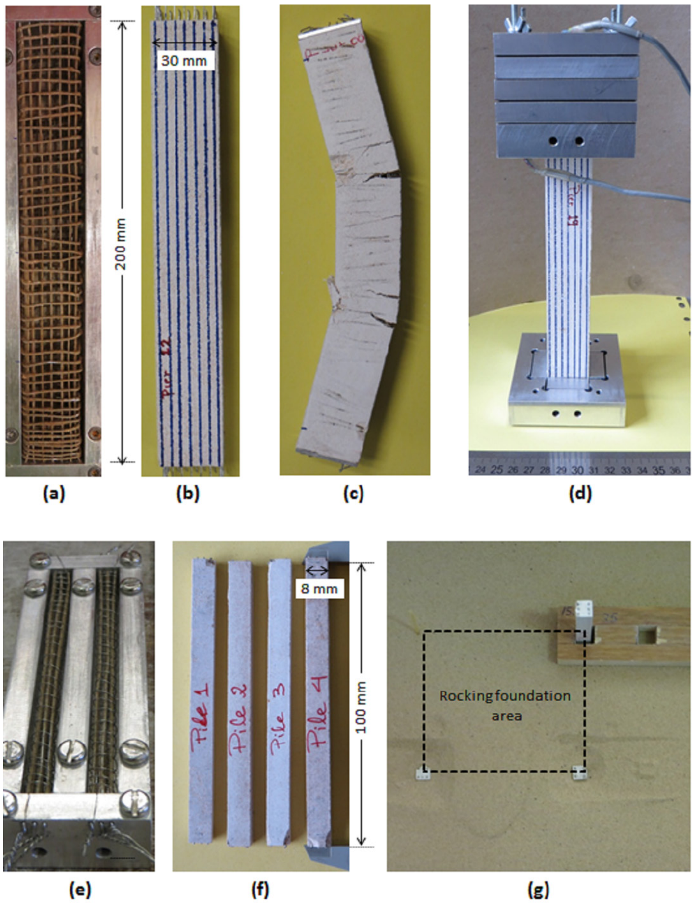

Figure 3.Construction of reinforced concrete model columns and piles: (a) pier column reinforcement within formwork; (b) and (c) pier column model before and after element testing; (d) the assembled deck-column-foundation model; (e) pile reinforcement in formwork; (f) RC pile models; and (g) pile placement procedure indicating the area that the foundation was placed upon.

Taking advantage of the effectiveness of the UoD earthquake simulator in reproducing desired motions, an ensemble of records from historic earthquakes were utilized as base excitation. Two different seismic scenarios were considered where the models were subjected to a series of successive ground motions. The herein presented results refer to the case where the seismic sequence involved a very strong earthquake followed by a number of lower magnitude motions, representing aftershocks. More specifically, the following sequence was used: the Rinaldi motion (1994 Northridge earthquake), the Aegion motion (1995 Aegion earthquake in Greece), the L'Aquila AM043 motion (2009 L'Aquila earthquake in Italy) and the test ended with the very destructive Takatori motion (1995 Kobe earthquake in Japan). Due to paper length limitations, the following presentation of results focuses on the response of the three studied systems to shaking with the first, very strong magnitude, motion (i.e. the Rinaldi).

Presentation of Results

All subsequent results in this paper will be given at prototype scale at 50-g.

Figure 4 shows the accelerations measured at the centre of mass of the deck in each of the three models. Also plotted are the demand motion, slip table motion and free field ground motion. As anticipated, thanks to its significantly lower moment capacity, the rocking pier experiences invariably lower acceleration than the other two (rocking isolation effect). As expected, the response of the pier lies between the two benchmark cases of conventional design and rocking isolation. Yet, the maximum acceleration developed in this hybrid system quite approximates the respective conventional value (0.37 g in comparison to 0.41 g, while the peak acceleration experienced by the rocking pier is only 0.28 g). This suggests that foundation improvement with piles and soil densification increased the total capacity quite a lot, in fact rather more than it was desirable as will be shown in the following.

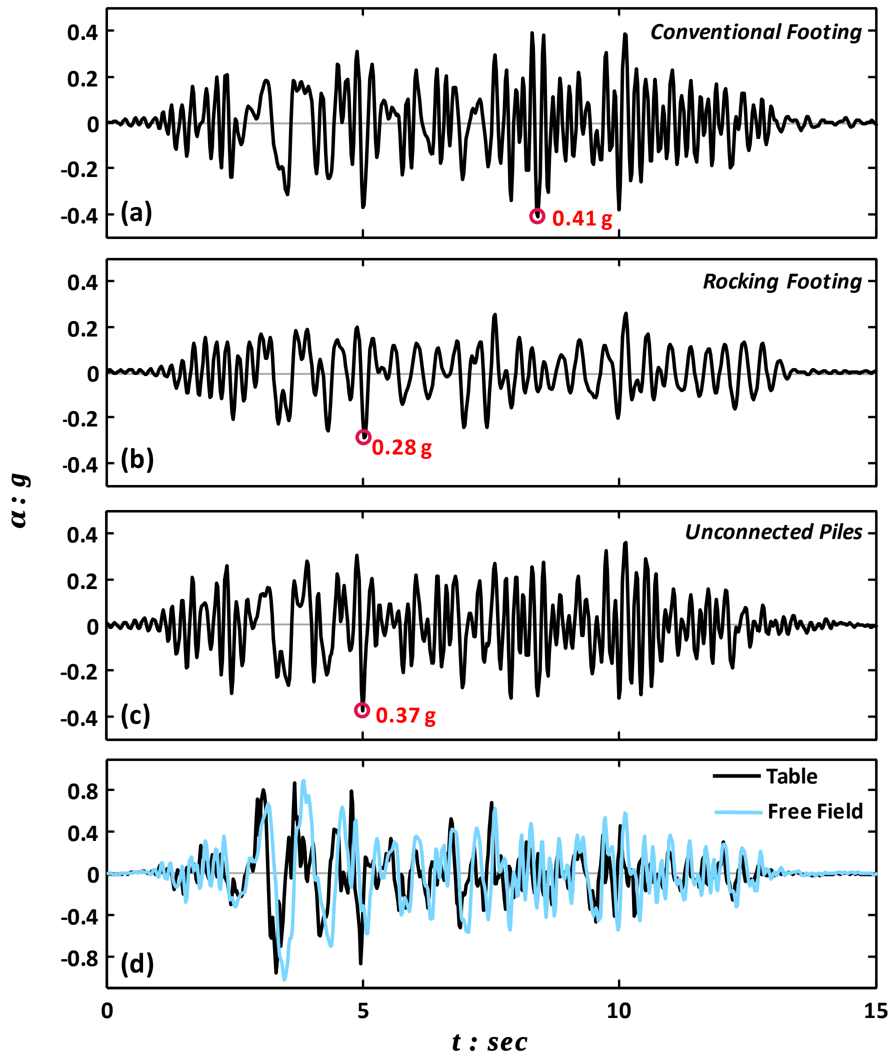

Figure 4. Acceleration time-history sequence recorded during shaking with the Rinaldi record (Northridge 1994): (a) deck of conventional pier (B = 7.5 m); (b) deck of rocking-isolated pier (B = 4 m); (c) deck of rocking-isolated pier on unconnected piles; and (d) excitation.

Recognizing this substantial increase in the capacity of the hybrid rocking system in comparison to the rocking footing is key for the evaluation of the differences in the three systems hysteretic performance summarized in Figure 5. Having somewhat larger capacity than would be required so as to fully isolate the superstructure, the hybrid foundation experiences less permanent rotation (Figure 5b) and less settlement (Figure 5c) than the rocking footing, yet at the cost of some considerable accumulation of flexural deformations at the column base (Figure 5a). In contrast to the rocking footing, where the RC column responds practically elastically, the column of the hybrid system seems to suffer significant plastic deformations consuming about 30% of its ductility capacity (the latter is deduced by section analysis and indicated by the backbone blue coloured curve). Even so, this performance is superior to the performance the conventional system which suffers excess structural distress, consuming about 80% of its ductility capacity.

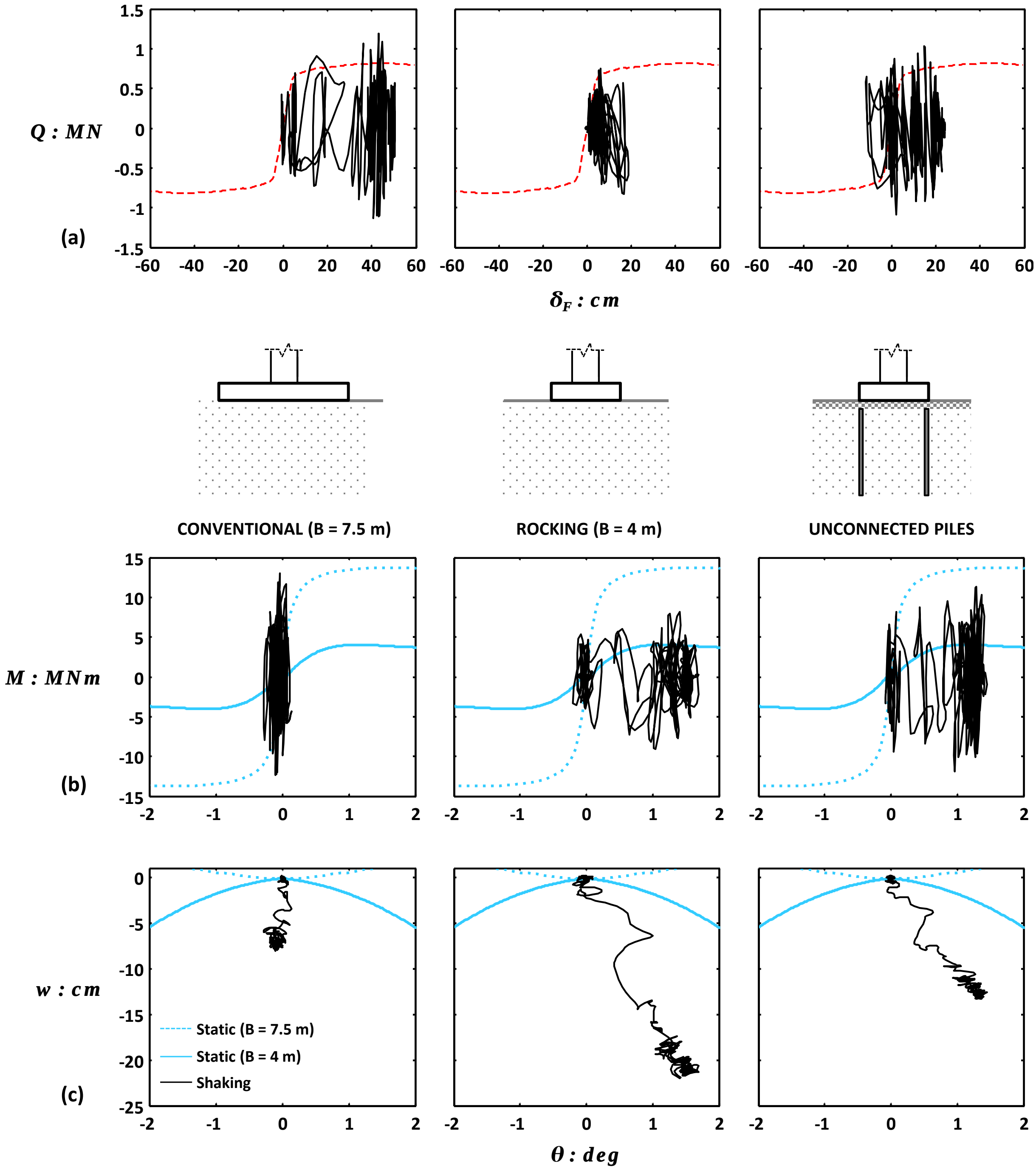

Figure 5. Comparison of the hysteretic performance of the rocking pier on unconnected piles with the response of the piers standing on the conventionally designed and the rocking isolated footings in terms of: (a) shear force *vs*. deflection (Q–δ_F) of the column base; (b) foundation moment *vs*. rotation (M–θ) and (c) settlement *vs*. rotation (w–θ). In each plot, the theoretical (analytical) static curve is superimposed on the dynamic loops.

Figure 6 compares the response of the three systems in terms of total deck drift, also serving in highlighting the different mechanisms of response. In agreement to previously made observations, the rocking pier deck deflections are almost exclusively due to foundation rotation while column deflection plays a minor role. The opposite is the case for the conventional pier. Interestingly, the pier rocking on unconnected piles demonstrates a combination of rocking motion with column flexural deformation. More specifically, during the first about 7 seconds of motion the rocking mode of response prevails while thereafter the response is characterized by significant built-up of column damage. As a result, system C ends up with almost the same total deck drift as the conventional design while System B certainly demonstrates and advantageous performance as far as deck deflections are concerned.

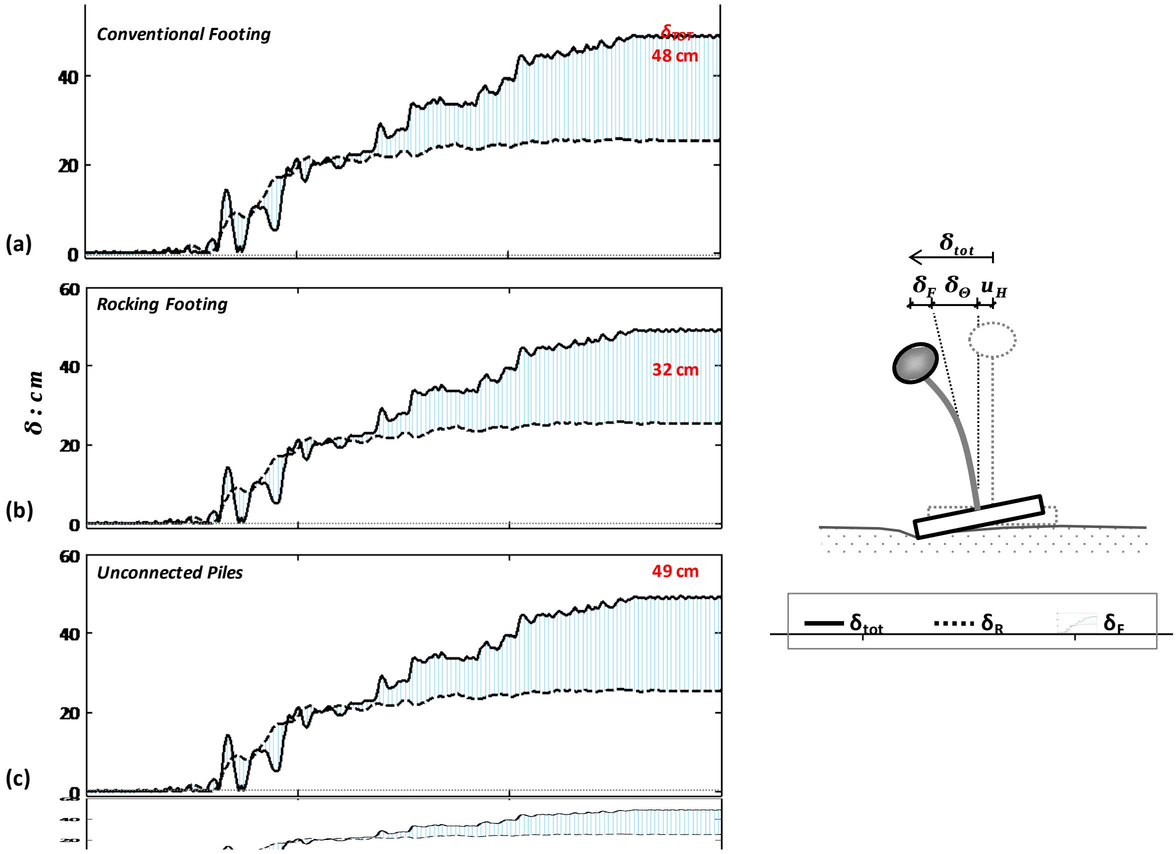

Figure 6.Total deck drift (δ_{tot}), shown as the components of rotational movement (δ_R) and flexural deformation (δ_F), during shaking with the Rinaldi record (Northridge 1994) for : (a)the conventional pier; (b) the rocking pier; and (c) the pier rocking on unconnected piles.

Although detailed presentation of the response during the following earthquake motions exceeds the purposes of this paper, it is important to note that after the Rinaldi earthquake the pier on unconnected piles continued to respond in a similar way, combining rocking motion with structural deformation at the base of the column and eventually collapsed during shaking with the Takatori record. Figure 6 shows photos of the model after the test indicating dramatic structural collapse combined with significant uplifting if the foundation. During excavation of the model, the piles were found evidently displaced and rotated. This indicates significant contribution of the pilesin increasing the total moment capacity of the foundation system.

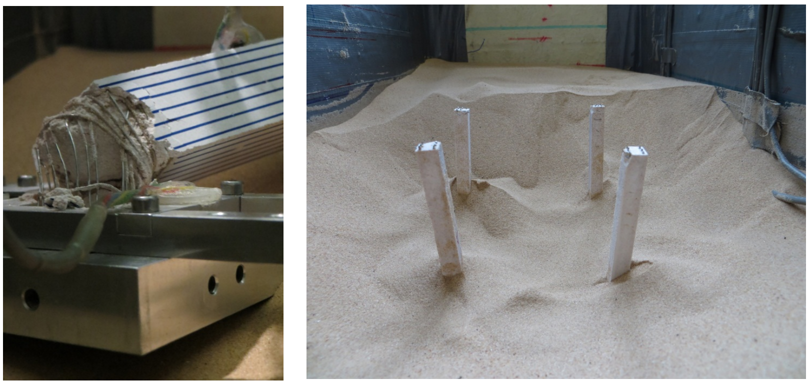

Figure 6.Photos of the pier on unconnected piles model after testing.

Conclusions

Rocking isolation appears to have important potential in isolating bridge piers from excess structural deformation and preventing failure during strong earthquakes. The sole drawback is associated with considerable settlement accumulation which, however, can be mitigated through soil improvement and the use of hybrid foundation systems as the one investigated in this paper. Yet, particular care must be taken in the design of such systems to avoid increasing the total capacity of the foundation by such amount as to partially cancel the rocking isolation effect and transfer significant distress on the superstructure.

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